2. Major decision variables

The major decision variables include new wind capacity, wind storage, conventional capacity, and dispatch of conventional capacity.

Note: Variables that denote capacity are expressed in megawatts and begin with capital letters. Variables that denote energy are expressed in megawatthours and begin with lower-case letters.

Wind

There are three types of wind capacity in WinDS—onshore, shallow offshore, and deep offshore. They are distinguished by different costs (capital and operating) and performance (capacity factors). Within each of these types, there are additional categories—based on whether the wind generation is transmitted on existing[1] (in 2000) transmission lines or new transmission lines built specifically for the wind generation. Wind generation transmitted on new dedicated transmission lines is further disaggregated into that used within the same region as the wind site, and that transmitted from one wind supply/demand region to another.

Onshore wind

$WturN_{i,wscp}$ New[2] onshore wind turbine capacity (MW), able to be connected to existing transmission lines from region i at a cost associated with step wscp of the transmission supply curve. This variable does not have a subscript that denotes the class of wind, because the next class of wind to be used from region i is selected before the LP is run for the current period; i.e. in WinDS, only one class of onshore wind on existing lines is allowed to be built in any specific region in any one 2-year period. This is done to reduce the number of variables in the LP.

$WturTN_i$ New onshore wind turbine capacity (MW) that can be transmitted only on new transmission lines dedicated to wind transmission from region i to another region. This variable does not have a subscript that denotes the class of wind, because the next class of onshore wind on new lines to be used from region i is selected before the LP is run for the current period. This variable does not have a wscp subscript, because there is no supply curve associated with building dedicated transmission all the way to the destination region (as opposed to building to a connecting point with the existing grid). The new transmission for this new wind capacity is assumed to be built from the center of region i to the center of a different destination region.

$Wtur\_inregion_{c,i}$ New onshore wind turbine capacity (MW) whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i, i.e. the new transmission line is built directly to a distribution system within region i, not to the electric transmission grid.

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[1] For the purposes of this document, the word "existing" means in existence at the start of the modeled time, i.e. in existence in the year 2000.
[2] New capacity means capacity built in this period, i.e. in this period's optimization run of the linear program.

$WN_{i,j}$ New onshore wind turbine capacity (MW) in region i that is transmitted to region j by connecting to the existing transmission grid. This variable allows WinDS to track the source of all wind coming into a region j so that dispersion of wind supplies can be accounted for in calculating the variance in the wind output. This variable differs (has a value less than or equal to) from $WturN_{i,wscp,}$ in that some of the capacity represented by $WturN_{i,wscp}$ may be used to supply energy to storage (e.g., electrolyzers/hydrogen storage) and is not transmitted directly to the grid.

$WTN_{i,j}$ New onshore wind turbine capacity (MW) in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission. This variable differs (has a value less than or equal to) from $WturTN_i$, in that some of the capacity represented by $WturTN_i$ may be used to supply energy to storage (e.g., electrolyzers/hydrogen storage) and is not transmitted directly to the destination region.

$WNSC_{i,wscp}$ New onshore wind turbine capacity (MW) to be connected to the grid in region i from step wscp of the supply curve, which provides the cost of building transmission from region i to the grid. There is no wind class subscript, because only one class is permitted from each region in each period. By separating this variable from $WN_{i,j}$ (i.e., not having a variable $WN_{c,i,j}$ with three subscripts), the total number of variables is reduced.

$WELEC\_inregion_{c,escp,i}$ New onshore wind turbine capacity (MW) from a class c wind site on step escp of the supply curve within region i that is transmitted on new transmission lines to a load center also within region i. This is also the transmission line capacity built from the wind site to the load center within the same region i. This variable differs (has a value less than or equal to) from $Wtur\_inregion_{c,i,}$ in that some of the capacity represented by $Wtur\_inregion_{c,i}$ may be used to supply energy to storage (e.g., electrolyzers/hydrogen storage) and is not transmitted directly to the grid.

$wind\_2\_electrolysis_{c,i,s}$ Class c wind generation (MWh) from new wind turbines that connect to the grid (not directly to load distribution systems) supplied to the new conversion to storage (e.g., electrolyzers/hydrogen storage) in season s in region i.

$grid\_2\_welectrolysis_{i,m}$ Grid-supplied electricity (MWh) to new wind storage (e.g., electrolyzers/hydrogen storage) at grid-connected wind farms in region i in time slice m.

$wind\_2\_electrolysis\_inregion_{c,i,s}$ Wind-generated electricity (MWh) from class c new turbines in region i in season s that goes to storage (e.g., electrolyzers/hydrogen storage) at a wind site that is not connected to the grid, but is connected by new lines directly to the distribution system at a load center.

$grid\_2\_welectrolysis\_inregion_{i,m}$ Grid-supplied electricity (MWh) to new wind storage (e.g., electrolyzers/hydrogen storage) at “inregion” wind farms in region i in time slice m.

WCt_g New onshore national wind turbine capacity (MW) in bin g; used for estimating the increase in wind turbine price with rapid world growth

$WCtinst_{ginst,i}$ New onshore wind turbine capacity (MW) from bin ginst in region i; used for estimating the increase in installation costs with rapid regional growth

Shallow offshore wind

The shallow offshore wind variables are similar to the onshore variables, with the exception that on-site storage (e.g., electrolyzers/hydrogen storage) is not allowed.

$WturNofs_{i,wscpofs}$ New shallow offshore wind turbine capacity (MW), able to be connected to existing transmission lines from region i at a cost associated with step wscpofs of the transmission supply curve. This variable does not have a subscript that denotes the class of wind, because the next class of shallow offshore wind to be used from region i is selected before the LP is run for the current period, i.e. in WinDS only one class of shallow offshore wind on existing lines is allowed to be built in any specific region in any one 2-year period. This is done to reduce the number of variables in the LP.

$WturTNofs_i$ New shallow offshore wind turbine capacity (MW) that can only be transmitted on new transmission lines dedicated to wind transmission from region i to another region. This variable does not have a subscript that denotes the class of wind, because the next class of shallow offshore wind on new lines to be used from region i is selected before the LP is run for the current period. This variable does not have a "wsc" subscript, because there is no supply curve associated with building dedicated transmission all the way to the receiving region (as opposed to building to the nearest grid connection). The new transmission is assumed to be built from the center of region i to the center of a different destination region.

$Wtur\_inregionofs_{c,i}$ New shallow offshore wind turbine capacity (MW) whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i, i.e., the new transmission line is built directly to a distribution system within region i, not to the electric transmission grid.

$WNofs_{i,j}$ New shallow offshore wind turbine capacity (MW) in region i that is transmitted to region j by connecting to the existing transmission grid. This variable allows WinDS to track the source of all wind coming into a region j, so that dispersion of wind supplies can be accounted for in calculating the variance in the wind output.

$WTNofs_{i,j}$ New shallow offshore wind turbine capacity (MW) in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission.

$\mathbf{WELEC\_inregionofs_{c,escp,i}}$ New shallow offshore wind turbine capacity (MW) from class c wind site from supply step escp within region i that is transmitted on new transmission lines to a load center also within region i. This is also the transmission line capacity built from the wind site to the load center within the same region i.

$\mathbf{WNSCofs_{i,wscpofs}}$ New shallow offshore wind turbine capacity (MW) connected to the grid in region i from step wscpofs of the supply curve, which provides the cost of building transmission from region i to the grid. There is no wind class subscript, because only one class is permitted from each region in each period. By separating this variable from $WNofs_{i,j}$ i.e. not having a variable $WNofs_{c,i,j}$ with three subscripts, the total number of variables is reduced.

Deep offshore wind

The deep offshore wind variables are similar to the onshore variables with the exception that on-site storage (e.g., electrolyzers/hydrogen storage) is not allowed.

$\mathbf{WturNofd_{i,wscpofd}}$ New deep offshore wind turbine capacity (MW), able to be connected to existing transmission lines from region i at a cost associated with step wscpofd of the transmission supply curve. This variable does not have a subscript that denotes the class of wind, because the next class of deep offshore wind to be used from region i is selected before the LP is run for the current period, i.e. in WinDS, only one class of deep offshore wind on existing lines is allowed to be built in a region in any one 2-year period. This is done to reduce the number of variables in the LP.

$\mathbf{WturTNofd_{i}}$ New deep offshore wind turbine capacity (MW) that can only be transmitted on new transmission lines dedicated to wind transmission from region i to another region. This variable does not have a subscript that denotes the class of wind, because the next class of deep offshore wind on new lines to be used from region i is selected before the LP is run for the current period. This variable does not have a wscp subscript, because there is no supply curve associated with building dedicated transmission all the way to the receiving region (as opposed to building to the nearest grid connection). The new transmission is assumed to be built from the center of region i to the center of a different destination region.

$\mathbf{Wtur\_inregionofd_{c,i}}$ New deep offshore wind turbine capacity (MW) whose transmitted electricity will move on new transmission lines dedicated to wind from a class c wind site within region i to a load center also within region i, i.e., the new transmission line is built directly to a distribution system within region i, not to the electric transmission grid.

$\mathbf{WNofd_{i,j}}$ New deep offshore wind turbine capacity (MW) in region i that is transmitted to region j by connecting to the existing transmission grid.

This variable allows WinDS to track the source of all wind coming into a region j, so that dispersion of wind supplies can be accounted for in calculating the variance in the wind output.

$WTNofd_{i,j}$ New deep offshore wind turbine capacity (MW) in region i that is transmitted to region j by a new transmission line built for and dedicated to wind transmission.

$WELEC\_inregionofd_{c,escp,i}$ New deep offshore wind turbine capacity (MW) for a class c wind site from supply step escp within region i that is transmitted on new transmission lines to a load center also within region i. This is also the transmission line capacity built from the wind site to the load center within the same region i.

$WNSCofd_{i,wscpofd}$ New deep offshore wind turbine capacity (MW) to be connected to the grid in region i from step wscpofd of the supply curve, which provides the cost of building transmission from region i to the grid. There is no wind class subscript, because only one class is permitted from each region in each period. By separating this variable from $WNofd_{i,j}$ i.e., not having a variable $WNofd_{c,i,j}$ with three subscripts, the total number of variables is reduced.

Wind storage

ELE_i New capacity (MW) at the onshore wind site in region i for converting the wind-generated electricity to the storage medium. For hydrogen, ELE represents the electrolyzer capacity.[3]

$H2storagecapacity_i$ New storage (hydrogen) capacity in region i.

$fcellcapacity_i$ New generation capacity (MW) fueled by the storage medium generated from onshore wind in region i. For hydrogen, this is the fuel cell capacity.

$fcell_{i,r,s}$ Electricity (MWh) generated from new wind storage (e.g., electrolyzers/hydrogen storage) in wind supply region i for use in NERC region r during season s. Because it is assumed that the stored energy is converted to electricity only during the peak electric time slice of each season, it is not necessary to keep track of the specific time slice during which the stored energy is used to produce electricity, but only the season. The destination of the stored energy is tracked only to the NERC region destination to reduce the number of decision variables.

$fcell\_inregion_{c,i,s}$ Electricity (MWh) generated from new wind storage (e.g., electrolyzers/hydrogen storage) filled by class c wind resources in wind

[3] All the variable names associated with wind storage are based on hydrogen. For example, ELE stands for electrolyzer. However, they can also represent the conversion necessary for other forms of storage. For example, in a compressed-air energy system, ELE would be the compressor needed to convert the wind-generated electricity to compressed air.

supply region i for use in the same wind demand region i during season s. The class subscript c ensures that an energy balance can be maintained by wind class between the amount of wind energy coming into storage from each wind class and the amount going out of storage. Because wind storage is assumed to be used to generate electricity only during peak electric-load time slices, the seasonal subscript s completely defines the time slice in which the generation occurs.

$fcelldest_{n,s}$ Electricity (MWh) generated from new wind storage (e.g., electrolyzers/hydrogen storage) consumed in PCA n in season s. Inasmuch as wind storage is assumed to be used to generate electricity only during peak electric-load time slices, the seasonal subscript s completely defines the time slice in which the generation occurs. This variable could have been subscripted i,n,s and replaced the variable $fcell_{i,r,s}$, but that would have added more than 175,000 more variables (4*358*[136-13]) (see the constraint "FUEL_CELL_BALANCE" in the equations that follow this section)

$HEGBIN_{hebp}$ New national capacity (MW) for conversion from wind generation to stored energy (i.e. electrolyzer capacity) in growth bin hebp; used for estimating the increase in price with rapid growth.

$HFCGBIN_{hfcbp}$ New national capacity (MW) for conversion from stored energy to electricity in growth bin hfcbp (i.e. fuel cell capacity); used for estimating the increase in price with rapid growth

Hydrogen fuel

hfs_i Hydrogen fuel (kg) produced in region i from new onshore wind installations that are connected to the grid.

hfd_j Hydrogen fuel (kg) consumed in region j and produced by new wind installations connected to the grid.

$hf_{i,j}$ Hydrogen fuel (kg) shipped from new onshore wind installations in region i that are connected to the grid to region j.

$hf\_inregion_{c,hscp,i}$ Hydrogen fuel (kg) produced from class c wind in region i from step hscp for the supply curve that provides the cost of hydrogen shipment from wind in the region to city load centers within the same region i.

$HF\_DISELEC\_CAP_j$ New distributed storage (e.g., electrolyzers/hydrogen storage) capacity (kg/year) powered by the grid and located at load center j (as opposed to ELE_j, which is powered by wind and the grid and located at a wind site).

$hfdiselec_j$ Hydrogen fuel (kg) produced by both new and old distributed electrolyzers in region j for use as a transportation fuel. Does not include hydrogen stored for use in a distributed fuel cell.

$hfdiselec\_2\_fcell_{j,m}$ Hydrogen fuel (kg) produced by both new and old distributed storage (e.g., electrolyzers/hydrogen storage) in region j for storage for later use in a generator (e.g., fuel cell) in time slice m.

$HF\_STEAMREF\_CAP_j$ New steam methane reformer capacity (kg/year) in region j.

$hfsteamref_j$ Hydrogen fuel (kg) produced by both new and old steam methane reformers in region j.

$DISFCELL\_CAP_n$ New distributed fuel cell capacity (MW) within PCA n using hydrogen from the distributed electrolyzers $HF\_DISELEC\_CAP_j$ and steam methane reformers $HF\_STEAMREF\_CAP_j$ that are in demand regions j within PCA n. These distributed fuel cells are accounted for at the PCA level (n) rather than the wind supply/demand region level (j) to reduce the number of variables.

Conventional generation

$CONVCAP_{n,q}$ Total conventional capacity (MW) in PCA n[4] of type q.

$CONVGEN_{m,n,q}$ Total conventional capacity (MW) from plants of type q operating in time slice m in PCA n.

$CONVPGEN_{m,n,q}$ Total conventional capacity (MW) from plants in PCA n of type q that is in excess of the conventional generation that operates in nonpeak time slices ($CONVPGEN_{m,n,q}$. will be zero for off-peak time slices). This variable allows additional costs to be incorporated for the use of base and intermediate load technologies that are operated at higher levels during peak time slices than in other time slices. These additional costs reflect the fact that for a coal plant to generate more power on peak, it will have to buy fuel to ramp up before the peak time slice and down after the slice (WinDS also includes a constraint that ensures that any base generator incurs the costs

[4] Note that, for conventional capacity, the decision variable is not the new capacity, but the total capacity. This was done to simplify bookkeeping and to eliminate the need for vintaging of capacity built after 2000. To ensure that conventional capacity from previous periods (minus retirements) is built, a lower bound is specified for each of these variables. The objective function value from the LP is inaccurate, in that the cost of the conventional generators is incurred each period, but this does not affect the amount of conventional capacity installed, because anything built beyond the lower bound must pay the marginal cost of new capacity. It does affect the amount of conventional fuel purchased, in that the old capacity is assumed to have the same heat rate as the new capacity. On the other hand, it does ensure that the marginal cost of new capacity accurately reflects the heat rate of the newest units. For coal-fired generators, vintage is tracked through the existence of four types of coal plants, pre-2000 plants with scrubbers, pre-2000 plants without scrubbers, post-2000 pulverized coal plants, and post-2000 integrated gasification combined cycle plants.

associated with $CONVPGEN_{m,n,q}$ by preventing $CONVGEN_{m,n,q}$ from being larger in peak time slices than in the average of the two shoulder time slices surrounding the peak).

$coalowsul_{n,q}$ Total conventional generation (MWh) from coal plants in PCA n of type q using low-sulfur coal.

QSq,n Total capacity (MW) in PCA n of type q that has been modified to provide quick-start capability.

$SR_{m,n,q}$ Total spinning reserve capacity (MW) available in time slice m in PCA n by generator type q.

Dispatchable load

IL_n Interruptible load (MW) in PCA n

$ILt_{ilg,n}$ Interruptible load (MW) from supply curve step ilg used in PCA n.

Transmission

$CONVT_{m,n,p}$ Total conventional capacity (MW) transmitted in time slice m from PCA n to PCA p.

$WT_{n,p}$ Total wind capacity (MW) transmitted from PCA n to PCA p.[5]

$TPCAN_{n,p}$ New transmission line capacity (MW) built to carry new generation between PCA n and PCA p.

$CONTRACTCAP_{n,p}$ Total firm capacity (MW) contracted to be supplied to PCA n by PCA p.

$TPCA\_Ct_{tpca\_g}$ New transmission capacity (MW) in growth bin tpca_g; used for estimating the increase in new transmission line price with rapid growth.

[5] Without this variable, WinDS will ship power from wind supply region i to the closest wind demand region j; and, from there, continue to ship it as conventional power to other PCAs where generation is needed. The problem with this is that if new lines are required for this extended wind transmission to a different PCA, the wind will not have to pay for a dedicated transmission line, i.e. the transmission line cost will be spread over more hours than only those during which the wind blows.